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DOSIMETRY AND DOSE DISTRIBUTION IN CESIUM-137 IRRADIATION UNIT USED AT THE EASTERN REGIONAL RESEARCH CENTER

ABSTRACT

A self-contained, cesium-137 Research Irradiator with the strength of approximately 147,000 Ci is located at the Eastern Regional Research Center (ERRC). When the irradiator was installed, the absorbed dose in a reference position of the irradiation field was calibrated and the absorbed doses in other locations of the irradiation field relative to the calibrated positions were measured to map its irradiation field. Self-read pocket dosimeters for gamma-ray were calibrated with a 120 M Ci Calibration Cs-137 source which delivered about 50 mR exposure during a 20-min irradiation at 50 cm from the source. A ferrous sulfate/cupric sulfate solution was used to calibrate the dosimetry of the irradiation chamber which holds three number 10 cans (16 cm inside diameter X 17.5 cm height each). At 20-min exposure, Dmax:Dmin = 1.35, except at the top and bottom 1/3 portions of the cans, all positions received a more or less uniform dose (about 0.13 kGy/min) during irradiation. A straight line of total dose (kGy) vs time (min) was constructed following the equation $y = 0.127x + 0.137$ with $r = 0.99$, where y is the total dose, and x is time. Radiochromic films and PVC strips were also used to monitor the irradiation operation after comparing results obtained from the chemical dosimeter. Two equations were constructed, respectively, as follows: $y = 0.0091x + 0.0015$ with $r = 0.99$, where y = absorbance and x = time (min), and $y' = 0.0041x' + 0.0185$ with $r = 0.99$, where y' = absorbance and x' = time (min). Controlled environment is important when such chemical and solid state dosimeters are used during irradiation at subfreezing, refrigerated, or ambient temperature conditions; the equipment has this capability.

KEYWORDS

Dosimeter; cesium-137 Irradiator; gamma irradiation; irradiation

INTRODUCTION

As a result of the transfer of the food irradiation program from the U.S. Army to the U.S. Department of Agriculture in October 1980, the Eastern Regional Research Center (ERRC) acquired a self-contained, cesium-137 Research Irradiator. During installation of the irradiator at ERRC, modifications were made to improve convenience of operation, to protect the control panel against radiation effects, and to provide better control of temperature of the food products being irradiated. This paper describes the irradiator as it is used at ERRC at the present time.

A map of the radiation field of this irradiator was not available. Thus, the first task after installation was to prepare such a map.

Different dosimeters were used to measure the absorbed dose in the cylindrical sample compartment of the irradiator: a) Fricke dosimeters (ferrous sulfate solutions) for temperatures $\geq 0°C$ for doses up to 0.4 kGy; b) ferrous sulfate/cupric sulfate ($FeSO_4/CuSO_4$) dosimeters for temperatures $\geqq 0°C$ for doses up to 7.0 kGy; and c) radiochromic film dosimeters for temperatures $<0°C$. Using these dosimeters the isodose curves were determined in vertical and horizontal positions within the sample compartment.

The ERRC cesium-137 Irradiator is an efficient research irradiator for small number of food samples per single run, with a maximum capacity of three samples up to 2.0 kg product each, for a single irradiation run. The irradiator has been successfully used for irradiation treatment of fresh meat and poultry at 0-4°C in the dose range of 1 to 10 kGy, vacuum-packed bacon from 7.5 to 30 kGy, and frozen bacon at -40°C from 7.5 to 30 kGy, and other applicable research at ERRC.

DESCRIPTION OF FACILITY

Cesium-137 Gamma Irradiator

This irradiator is a self-contained "Category I" radiation source. The irradiators of this category are those heavily shielded units having "no open position" (self-contained) and around which there are no significant radiation fields. As such they provide a high degree of safety to the operators against accidental radiation exposure.

This unit was manufactured by Lockheed Georgia Company[1] in 1969, with an initial strength of 213,000 Ci of cesium-137 for the U.S. Army Natick Research and Development Center in 1970, and subsequently transferred to the USDA, ERRC in November 1981. As of February 1984, the strength of the source was 147,000 Ci. Figure 1 is the front view of the irradiator. Initially the control panel was located in the front top of the irradiator and was subject to corrosion by ozone generated by the radiation. Therefore, during installation the control panel was removed from the irradiator, completely remodeled and rewired, and installed outside the irradiator as shown in Fig. 2. This figure also shows the opened loading-unloading part of the irradiator, which can accomodate three number 10 cans (16 X 17.5 cm each) on top of each other as the holders of the food samples for irradiation. Figure 3 presents an overall drawing of the irradiator. It consists basically of three parts: 1) Source holder and irradiation chamber, the lower part; 2) sample compartment including loading and unloading section, the middle part; and 3) the driving mechanism, the upper part. Figure 4 presents the cross section of the irradiation chamber. The radiation source material is contained in pellet form within 23 pairs of rectangular stainless steel tubes. These tubes are arranged vertically in pairs (one on top of the other) concentrically around the irradiation chamber's internal perimeter (see Fig. 3). The bars are doubly encapsulated by 316 LC stainless steel with the outer layer having a dimension of 1.085 X 13.344 inch (2.756 X 33.894 cm) and the inner layer having a dimension of 1.033 X 12.812 inch (2.624 X 32.542 cm). The source bars were produced at the Oak Ridge National Laboratory by Union Carbide Nuclear Company. The cesium-137 source material is in the form of $^{137}CsCl$ with an energy level of 0.66 Mev and a half-life of 30.3 years. Cs-137 has a larger self-absorption (30-50%) as compared with Co-60 (10%). Cesium-137 is formed through thermal-neutron fission of ^{235}U or ^{239}Pu as a byproduct in nuclear reactors, and this is readily available and is possibly of lower cost than Co-60 (6, 10).

Temperature Control

At present our research mainly involves low-dose (up to 10 kGy) application at refrigeration temperatures (0-5°C) and medium dose (10-30 kGy) application at cryogenic temperatures (≈40°C). Each application involves precise temperature control. Samples irradiated at low dose levels (usually below 10 kGy) are packaged either loosely (aerobically) or vacuum packed in plastic water impermeable pouches which are then placed into metal cans or Dewar flasks. A cooling mixture of crushed ice and chilled water is then added to fill the voids between the samples and the containers. Depending on the amount of volume existing in the voids, it is possible to irradiate without interruption one whole broiler chicken per can up to 7 kGy while maintaining an internal sample temperature between 0 and 5°C as shown in Table 1. With this system of temperature control, the irradiation chamber has the capacity of irradiating three samples of this size simultaneously.

Medium and high-dose irradiation of foods necessitates the use of cryogenic temperatures during the irradiation process (11, 12). To provide temperature control at the desired setting, the irradiator is equipped with a thermostatically controlled liquid nitrogen (N_2) feed line. The N_2 supply line and thermostat control wiring enters the sample compartment through the top lead shield of the chamber as shown in Fig. 5. Cryogenic temperatures in the sample chamber can be controlled within a ±5°C range at a preset temperature of, for example, -40°C. However, only two metal cans can be used if proper circulation of coolant is to be maintained throughout the sample compartment (Fig. 5). The tripod upon which the two cans rest permits coolant passage beneath the bottom can as does each of the metal support discs which are perforated to improve coolant and air circulation.

System Operation and Safety Features

The design of the cesium-137 Irradiator includes an elaborate electronic interlock control system that ensures safety to personnel operating this irradiator. Total operation of the irradiator is conducted through a central control panel located beside the main device (Fig. 2) that includes the following features:

[1]Reference to brand or firm name does not constitute endorsement by the U.S. Department of Agriculture over others of a similar nature not mentioned.

1) Main Power Switch—controls power for all electrical components associated with the irradiator operation.

2) Control Power Switch—controls power to the control panel devices.

3) Control Power Light—an indicator light labeled "power" functions when this switch is on.

4) Key Operated, Manual, or Timer Switch—selects the mode of desired operation, either manual or timer (automatic). The "off" position is an electrical interlock with the control power switch.

5) "Up" and "Down" Indicator or Lights—indicate when the compartment (drawer) is at either of these positions.

6) "Raise," "Lower," and "Stop" Push Button Switches—controls the desired direction of movement in the sample compartment (drawer).

7) Elapsed Time Indicator and Present Switch—show the elapsed time when the sample is in the "down" position. The switch can be used for returning to the "up" position at a predetermined set time.

The safety interlock system is designed in such a way that failure of any electronic or mechanical components will not result in any accidental personnel exposure to radiation. Basically the interlock system operates as follows:

a) Before the sample compartment (drawer) can be lowered to the "down" or irradiate position, the external shield doors and the inner sample compartment door must be closed and locked. Likewise a metal plug locked in the sample compartment's shielded roof must be in place. The safety interlocks will not permit the lowering of the sample compartment into the irradiated position until these requirements are met.

b) The shield doors cannot be opened once the sample compartment leaves the "up" position and moves to the "down" position due to the presence of the safety interlocks.

c) Should a power failure occur, the shield doors are locked automatically due to the design of the interlock system. In the event of a power failure, the use of a hand wheel permits the safe manual raising of the sample compartment from the "down" (irradiate) position to the "up" position.

d) Electrical circuit breaders protect the wiring and electrical devices associated with the irradiator control and interlock systems from overload.

Calibration of Safety Related Dosimeter

In addition to the 147,000 Ci Cs-137 Irradiator, the facility at ERRC is also equipped with a 120 m Ci Cs-137 Panoramic Irradiator with a 120-cm diameter round rotating table which is used for calibration of each thermoluminescent dosimeter badge (3). Calibration of self-read pocket dosimeters involves placing each dosimeter on the rotating table surface 50 cm from the source which is located in the center of the table. After exposure to deliver a 50 mr dose, the dosimeters are read with the post-irradiation exposure reading being compared to the pre-irradiation reading. The difference between these two readings represents the actual dose absorbed by the pocket dosimeter. Table 2 provides an example of such absorbance reading. The readings show that a good correlation exists between the delivered dose and dosimeter reading within 5% error. Using such apparatus to calibrate the pocket dosimeters, one can save much time in contrast to the "desk top" dosimeter calibrator (source) which delivers about 50 mr in 24 hr using an outer ring of eight holes (2).

DOSE DISTRIBUTION AND MAPPING

Standardization of a Reference Position

Five-milliliter glass ampoules were filled with the Fricke solution and then flame sealed. These liquid dosimeters were placed between two phantom materials in representative locations throughout the sample compartment in the irradiator. For practical purposes, six ampoules were placed between phantom materials (13 X 17.5 cm each) with a 3-cm distance from each other. These materials were then placed in a number 10 can and irradiated for a 0.5-min period. The dose distribution of the Cs-137 Irradiator sample compartment involved the use of Fricke chemical dosimeters (ferrous sulfate solution) (1), or a primary dosimeter, placed at well-defined positions within this sample compartment (see Table 5a and Fig. 5). The positioning of the chemical dosimeters was followed by a 0.5-min exposure of these devices

in the Cs-137 radiation field. Three identical sets of dosimeters were positioned and irradiation for 1.0, 1.5, and 2.0-min intervals, respectively. The data generated from this dosimeter exposure is reported as total absorbed dose which can be broken down into terms of a transient dose and a exposure dose. Total absorbed dose = Transient dose + Exposure dose. The transient dose was determined by extrapolation of the curve to zero exposure time and was determined to be 0.018 kGy as shown in Fig. 6. In a similar way, a ferrous sulfate/cupric sulfate ($FeSO_4/CuSO_4$) solution (5) was used for measurement of absorbed dose in a defined position within the sample compartment as shown in Table 3. The absorbed doses presented in this table and graphically in Fig. 7 serve as calibration standards for measurement of solid-form dosimeters such as radiochromic film and film of polished heat-pressed polyvinyl chloride. From the dose rate curve, one can calculate the absorbed dose if exposure time and locations of the irradiated specimen in the sample compartment of the irradiator are known.

Solid Phase Dosimetry

One form of a solid phase dosimeter is the radiochromic film which consists of hexahydroxyethyl pararosanile nitrile impregnated in nylon (4). These dosimeters, 1 cm X 1 cm X 2 mil in thickness, were placed in an opaque envelope and subjected to gamma irradiation for a set time period. Radiochromic film contains an amino triphenylmethane dye which when subjected to ionizing radiation undergoes a photochemical decomposition followed by an intramolecular electron rearrangement to form a stable and deeply colored corresponding dye (blue color). The absorbance of the film following irradiation at various positions within each of the three sample containers is summarized in Table 4. An absorbance at 600 nm of 0.05 was equivalent to an absorbed dose of 0.65 kGy in the center of the middle can. (Should the absorbed dose exceed 10 kGy, it is recommended that the spectrophotometer be set at 510 nm.) Figure 8 provides an absorbance-time response curve derived from absorbance readings of the radiation-exposed radiochromic film based on the data in Table 4, positions 24 through 26. As shown in this graph, a linear relationship existed between the absorbance and time variables. One can accurately correlate the absorbance of the solid phase film with the absorbed dose using the liquid chemical dosimeter as shown in Fig. 9.

Depth Dose Distribution

To obtain both vertical and horizontal depth dose curves for the irradiator sample compartment, ferrous sulfate/cupric ($FeSO_4/CuSO_4$) sulfate chemical dosimeters or radiochromic film solid phase dosimeters were placed into the sample compartment at the desired positions and irradiated as above. The ferrous $FeSO_4/CuSO_4$ dosimeters were then irradiated for 20 min at 22°C. Table 5 showed that all dosimeter positions received a more or less uniform dose during the irradiation process except at the top of can number 1 and bottom of can number 3. In practice the total dose delivered to a position in the irradiation chamber represents the sum of exposed dose (dose rate X irradiation time) and transient dose. In the course of low-dose irradiation treatments of fresh commodities, the transient dose could constitute a significant portion of the total dose. Our studies revealed that the transient dose varied from position to position in the vertical plane.

In the horizontal positions the dose distribution was very homogeneous. The dose absorbed by the samples being irradiated was only about 1% to 2% higher at the peripheries of the sample compartments as compared with the center locations (Fig. 10).

Other Dosimeter Types

For absorbed doses exceeding 7 kGy, an extended range chemical dosimeter containing ferrous sulfate/cupric sulfate solution (six times Fe/Cu) is recommended (7). The polyvinychloride dosimeter is a film of polished heat-pressed PVC (Bakelite VSA 3310) especially prepared for use as a solid form dosimeter. The PVC film dosimeter turns from a clear and colorless state to a brown or green color following exposure to radiation. Immediately after irradiation, the film was developed by heating at 65°C for 15 min which stabilized the irradiation induced color. The PVC film was then cut and its absorbance at 395 nm measured using a spectrophotometer (8). In addition, the irradiated and heat-treated PVC film dosimeter can be evaluated for dose response through the use of an encoding/isodensitracer feature of a recording densitometer. "Go-no-go" dosimeters also used for monitoring irradiation dose exposure. Very recently a paper about Optic-Chromic Dosimeters published by Radak and McLaughlin (9) may be used for low-dose irradiation.

CONCLUSIONS

A self-contained, cesium-137 Research Irradiator with the strength of approximately 147,000 Ci is located at the Eastern Regional Research Center. The irradiator is efficient for the irradiation of three samples containing a maximum of 2.0 kg each. Controlled environment is important when product and dosimeter are used during irradiation at subfreezing, refrigerated,

or ambient temperature conditions; the equipment has this capability. The irradiator was successfully used for irradiation of fresh meat, poultry, bacon, and fish products.

In general, three different chemical dosimeters were used in the measurement of the absorbed dose in the sample compartment (24.8 X 64.1 cm) of the irradiator. Fricke ($FeSO_4$ solution) and $FeSO_4/CuSO_4$ chemical dosimeters can be used at food irradiation temperatures above or equal to zero. Transient dose of 0.018 kGy in the center of the sample compartment which holds three cans on top of each other (16 X 17.5 cm each can) was determined by using the Fricke dosimeter. For the measurement of the absorbed dose using $FeSO_4/CuSO_4$ dosimeter, the results showed that the dose accuracy within a narrow range (98 ± 2%) is only in the two-thirds central section of the sample compartment in the vertical positions; in addition, the dose distribution is very uniform in the horizontal positions. At the top and bottom locations the D_{max}/D_{min} is 1.35. An extended range ferrous sulfate/cupric sulfate (six times $FeSO_4/CuSO_4$) was used when a dose higher than 7 kGy was given. In addition, two different solid phase dosimeters were used for irradiation at subfreezing temperatures and above zero. Data generated from treatment of the solid radiochromic film dosimeter indicated that a linear relationship existed between absorbance and exposure time. For the purpose of practical use in monitoring the irradiation operation, one can correlate absorbance change of the film with the absorbed dose using the liquid chemical dosimeter. The PVC film dosimeter was used only as supplementary dosimeter.

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TABLE 1. TEMPERATURE CONTROL OF IRRADIATED PRODUCTS

Dose (kGy)	Temperature, °C			
	Cooling medium		Chicken breast[c]	
	In[a]	Out[b]	In[a]	Out[b]
1	0.9	0.7[c]	3.6	3.6
2	0.8	0.7[c]	2.4	3.6
3	1.0	1.1	3.1	4.9
4	1.1	1.2	2.8	4.1
7	1.0	3.8	3.8	3.8

[a]Pre-irradiation temperature.

[b]Post-irradiation temperature.

[c]Thermocouple probe inserted into center of chicken breast muscle.

TABLE 2. EFFECT LOW-DOSE IRRADIATION ON POCKET DOSIMETER

Dosimeter No.	Instrument reading		
		ΔMR	Ave.
1	46	42	44.0
2	50	52	51.0
3	46	46	46.0
4	48	50	49.0
5	47	46	46.5
6	43	49	46.0

TABLE 3. DOSE DEPENDENCE ON POSITION OF THE CAN IN THE SAMPLE COMPARTMENT USING $FeSO_4/CuSO_4$ DOSIMETER

Position[b]	Absorbed dose[a]			
	10 min	20 min	30 min	40 min
1-1	1.06	1.98	2.85	3.74
1-2	1.16	2.15	3.19	4.27
1-3	1.27	2.33	3.45	4.70
1-4	1.29	2.52	3.74	5.02
1-5	1.41	2.61	3.86	5.20
1-6	1.43	2.65	3.85	5.22
2-1	1.46	2.70	4.00	5.24
2-2	1.47	2.74	4.09	5.38
2-3	1.45	2.74	4.07	5.40
2-4	1.45	2.72	4.06	5.34
2-5	1.43	2.71	4.01	5.29
2-6	1.40	2.43	3.97	5.22
3-1	1.46	2.69	3.97	5.28
3-2	1.46	2.71	3.99	5.30
3-3	1.40	2.66	3.94	5.21
3-4	1.31	2.54	3.76	4.95
3-5	1.21	2.32	3.46	4.49
3-6	1.09	2.06	3.05	3.96

[a] Dose is in kGy.

[b] Top can labeled as 1-1, middle can as 2-1, and bottom can as 3-1 and so on.

TABLE 4. ABSORBANCE DEPENDENCE ON POSITION OF THE CAN IN THE SAMPLE COMPARTMENT USING RADIOCHROMIC FILM DOSIMETER

Position[a]	Absorbance at 600 nm			
	10 min	20 min	30 min	40 min
1-1	0.081	0.201	0.244	0.329
1-2	0.095	0.213	0.278	0.368
1-3	0.102	0.230	0.296	0.405
1-4	0.106	0.231	0.332	0.429
1-5	0.105	0.221	0.336	0.443
1-6	0.101	0.260	0.334	0.446
2-1	0.112	0.244	0.352	0.454
2-2	0.111	0.252	0.352	0.458
2-3	0.109	0.248	0.346	0.456
2-4	0.111	0.243	0.359	0.461
2-5	0.113	0.240	0.340	0.451
2-6	0.110	0.262	0.344	0.453
3-1	0.109	0.244	0.337	0.443
3-2	0.106	0.239	0.352	0.460
3-3	0.106	0.238	0.350	0.457
3-4	0.103	0.225	0.334	0.431
3-5	0.100	0.215	0.307	0.391
3-6	0.093	0.203	0.268	0.365

[a]Top can as 1-1, middle can as 2-1, and bottom can as 3-1 and so on.

TABLE 5. DEPTH DOSE DISTRIBUTION FOR CS-137 IRRADIATION. DOSIMETER POSITION IS PLOTTED AGAINST THE DOSE AT 10-MIN EXPOSURE. THREE NO. 10 CANS PACKED ON TOP EACH OTHER IN THE IRRADIATION CHAMBER

Can #	Dosimeter location		10 Min dose (kGy)[c]	Absorbed dose ratio[d] (%)
	Within can[a]	Distance from top of can #1 (cm)[b]		
1	Top	3.0	1.06	73
	Middle	8.9	1.28	88
	Bottom	14.8	1.43	98
2	Top	21.3	1.46	100
	Middle	27.2	1.45	99
	Bottom	33.1	1.41	97
3	Top	39.6	1.46	100
	Middle	45.5	1.36	93
	Bottom	51.4	1.10	75

[a]Refer to Fig. 4a for view of can placement in sample chamber.

[b]The top and bottom dosimeter for each can was, respectively, 3 cm from the top rim and 3 cm from the bottom rim.

[c]See Fig. 6 for graph of data.

[d]Absorbed dose ratio = calcuated by position within can: ((position absorbance) (maximum absorbance of all positions)) X 100.

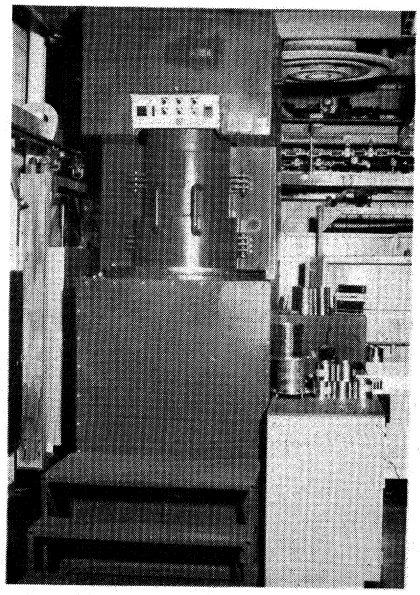

FIG. 1. Cesium-137 self-contained radiation source at ERRC, USDA, ARS. As of February 1984, the strength of the source is 147,000 Ci.

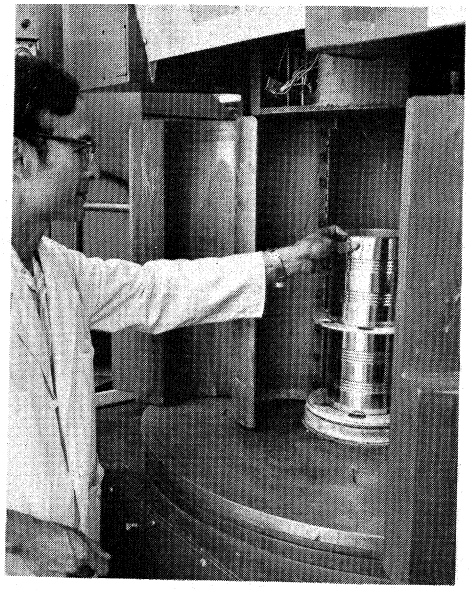

FIG. 2. Irradiation compartment of cesium-137 Irradiator. The compartment holds three number 10 cans on top of each other (16 X 17.5 cm each can).

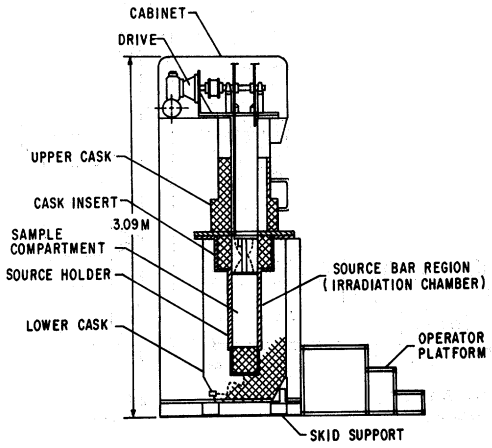

FIG. 3. Schematic drawing of cesium-137 Irradiator assembly.

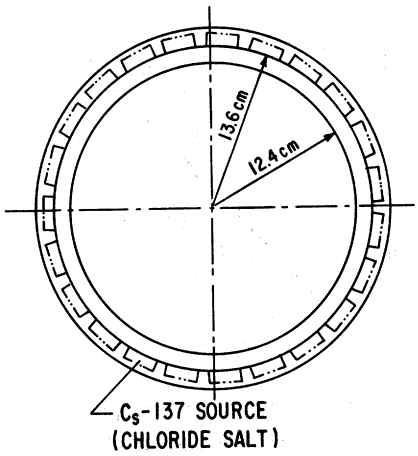

FIG. 4. Cross section of the source holder with the location of the Cs-137 source.

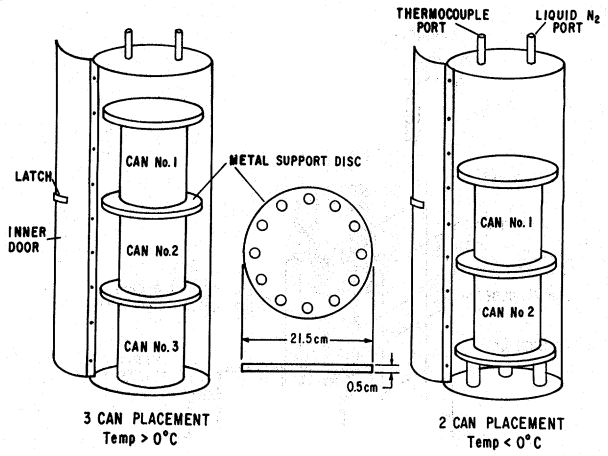

FIG. 5. Irradiator sample compartment. a) For refrigeration temperature use. b) For cryogenic temperature use.

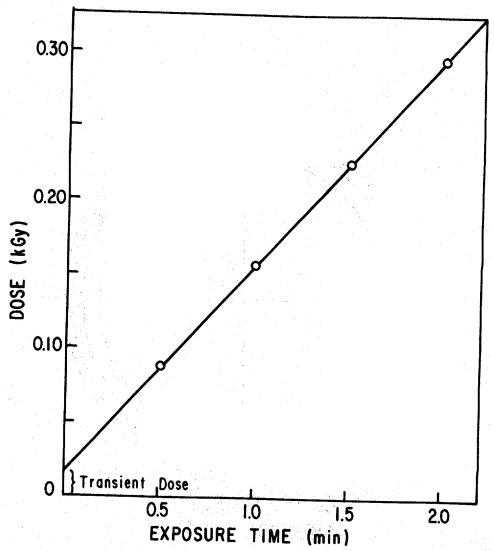

FIG. 6. Extrapolation of transient dose. The ferrous sulfate dose meter (Fricke dose meter) is used for effect vs dose.

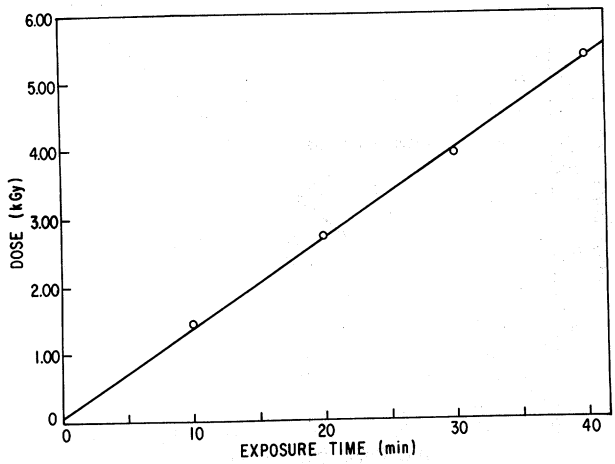

FIG. 7. Effect of radiaton on ferrous sulfate/cupric sulfate dosimeter. The dosimeters in the center of the middle metal can were selected for the dose meter response.

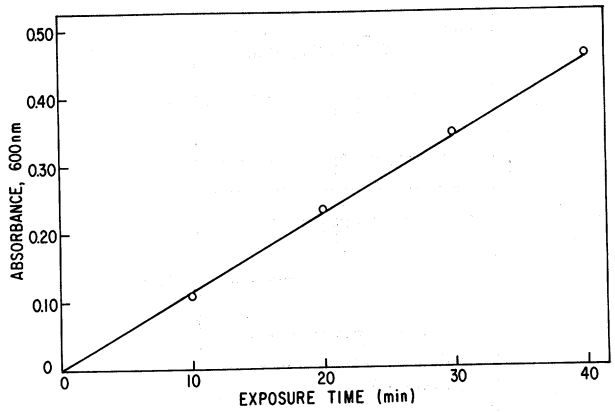

FIG. 8. Effect of radiation on radiochromic film dosimeter. By plotting the absorbance as a function of exposure time, the transient dose after conversion can be determined.

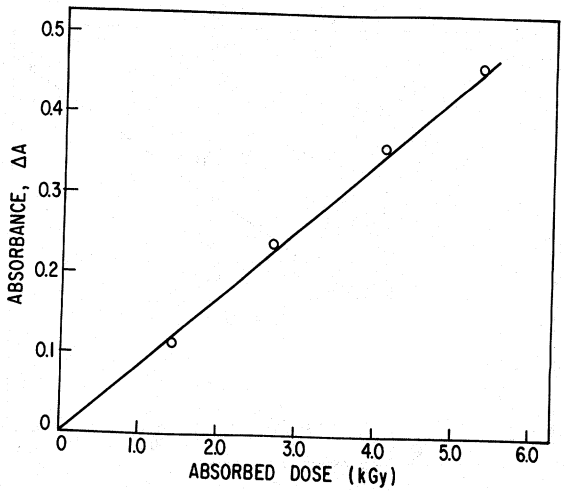

FIG. 9. Radiochromic film dosimeter response. The film dosimeter was calibrated against a ferrous sulfate/cupric sulfate dosimeter in the center of the middle metal can at irradiation chamber.

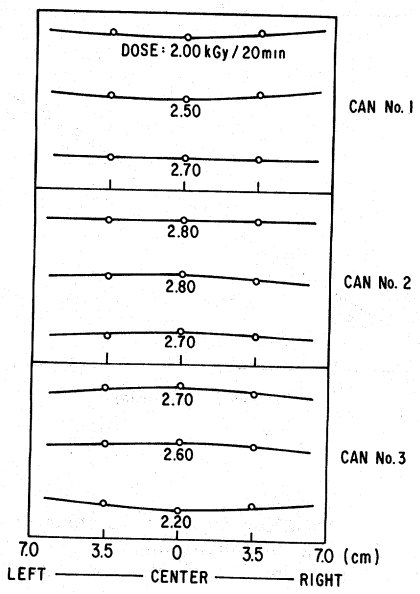

FIG. 10. Dose distribution for Cs-137 irradiation.